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Higgs, SUSY and the Standard Model at $\gamma\gamma$ Colliders ⋆

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Abstract

In this report I surveyed physics potential of the $\gamma\gamma$ option of a Linear e^+e^- Collider with the following questions in mind: *What new discovery can be expected at a $\gamma\gamma$ collider in addition to what will be learned at its 'parent' e^+e^- Linear Collider?* By taking account of the hard energy spectrum and polarization of colliding photons, produced by Compton back-scattering of laser light off incoming e^- beams, we find that a $\gamma\gamma$ collider is most powerful when new physics appears in the neutral spin-zero channel at an invariant mass below about 80% of the c.m. energy of the colliding e^-e^- system. If a light Higgs boson exists, its properties can be studied in detail, and if its heavier partners or a heavy Higgs boson exists in the above mass range, they may be discovered at a $\gamma\gamma$ collider. CP property of the scalar sector can be explored in detail by making use of linear polarization of the colliding photons, decay angular correlations of final state particles, and the pattern of interference with the Standard model amplitudes. A few comments are given for SUSY particle studies at a $\gamma\gamma$ collider, where a pair of charged spinless particles is produced in the s-wave near the threshold. Squark-onium may be discovered. An $e^\pm\gamma$ collision mode may measure the Higgs-Z-γ coupling accurately and probe flavor oscillations in the slepton sector. As a general remark, all the Standard Model background simulation tools should be prepared in the helicity amplitude level, so that simulation can be performed for an arbitrary set of Stokes parameters of the incoming photon beams.

Key words: Photon Linear Collider; Polarization; CP; Higgs; SUSY

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1 Why do we need a Photon Linear Collider?

The photon linear collider (PLC) makes use of the hard energy spectrum of the photons produced by Compton backscattering of a high power laser light off the linac e^- beam[1–3]. Therefore, a PLC should be considered as an option of a future e^+e^- Linear Collider. This observation naturally leads us to the following questions:

- *What new discovery can we expect at a Photon Linear Collider in addition to what we will learn at its 'parent' e^+e^- Linear Collider?*
- *Does the PLC option make a Linear Collider project more attractive?*

In this report, I try to find the answer to the above two questions.

I start my study by comparing the $\gamma\gamma$ channel with the e^+e^- annihilation channel, which are both source of various new particles. All charged particles are pair produced in both channels, and neutral particles can be produced as s-channel resonances. There is, however, an important difference in the spin of the accessible s-channel resonances. The e^+e^- annihilation channel cannot couple to a spin 0 resonance because of the electronic chirality conservation, whose breaking is suppressed by the tiny electron mass. The lowest spin of a particle that can be produced in the e^+e^- annihilation channel should hence be 1. On the other hand, the $\gamma\gamma$ channel can couple to a spin 0 resonance, while it cannot couple to a spin 1 resonance due to spin statistics of the $J_z = 0$ two-photon system[4]. It is this stunning difference between the two channels that makes a PLC complementary to e^+e^- colliders. We can probe the scalar sector in the s-channel of the colliding two photons at a PLC, whereas it can be probed only in association with another particle production at e^+e^- colliders. This possibility gives a PLC the unique potential of becoming the best observatory of the scalar sector, or the Higgs sector. We should take this opportunity very seriously, because the scalar sector is the least known sector of the Standard Model (SM), and because its detailed understanding is probably the most important key in our search for physics beyond the SM.

There are many excellent reports[5–8] on the role of a PLC as the laboratory of the Higgs sector, and I will give only a few general remarks in section 2. In addition to the precision measurements of the two-photon decay partial width and branching fractions of the Higgs bosons, I would like to emphasize the importance of probing new interactions, including CP violating ones, in the scalar sector. PLC is particularly well tailored for studying the CP property of resonances and interactions, because the two $J_z = 0$ two-photon initial states can form a CP-even and a CP-odd state, and they can be prepared by using linear polarizations of the laser beams. The power and limitation of PLC with linearly polarized laser beams are discussed. Once the Higgs property is

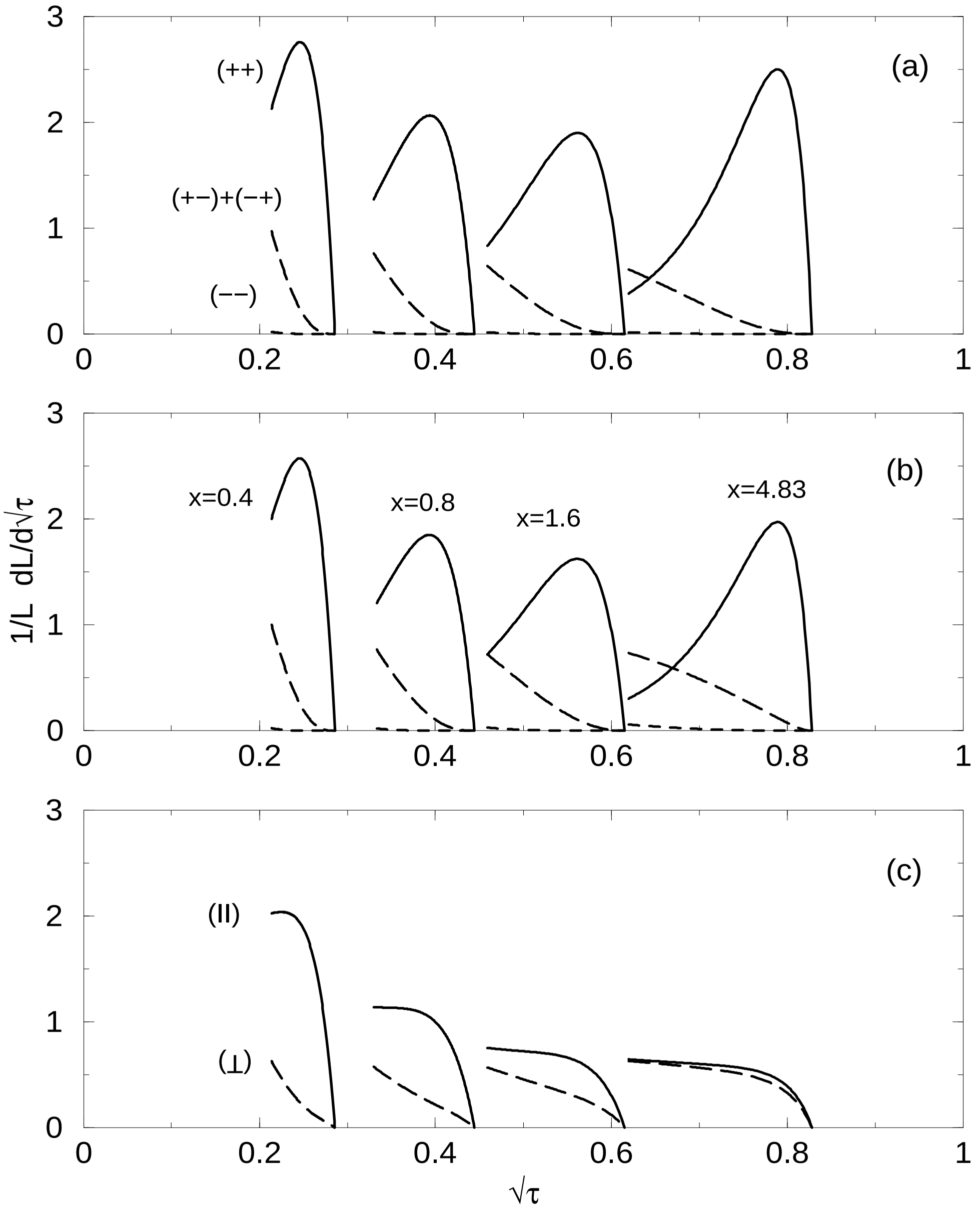

Fig. 1. Normalized luminosity functions of colliding photons as a function of $\sqrt{\tau} = \sqrt{s_{\gamma\gamma}}/\sqrt{s_{ee}}$, calculated in the Compton back-scattering limit. Four values of laser frequencies (w_o) are chosen, $x = 4E_e w_o/m_e^2 = 4.83$, 1.6, 0.8 and 0.4 from the right to the left. In (a) and (b), the luminosity is shown separately for the collisions of two right-handed photons denoted by solid lines $(++)$, those of right- and left-handed photons by long-dashed lines $(+-)+(-+)$, and those of two left-handed photons by short-dashed lines $(--)$. In (a), both photons are obtained by setting $P_e P_c = -1$, whereas in (b), they are obtained for $P_e P_c = -|P_e| = -0.8$. The curves in (c) are obtained for $P_e = 0$ and $P_t = 1$, when the two laser lights have parallel linear polarizations. Solid lines show collisions when two photons have parallel linear polarizations, and dashed lines are for two photons with perpendicular linear polarizations.

determined well in $\gamma\gamma$ collisions, measurement of the Higgs-γ-Z coupling may be done in the $e\gamma$ collision mode[9].

The role of a PLC in our study of supersymmetry is discussed in section 3. Because the available highest c.m. energy in the $\gamma\gamma$ mode is about 80% of the original e^+e^- collision c.m. energy,

$$\sqrt{\tau} = \frac{\sqrt{s_{\gamma\gamma}}}{\sqrt{s_{ee}}} < \frac{x}{x+1} < \frac{2+2\sqrt{2}}{3+2\sqrt{2}} \approx 0.83\,, \tag{1}$$

one generally expects that the e^+e^- mode is the discovery channel for those SUSY particles which may escape detection at the LHC. Here $x = 4E_e w_o/m_e^2$ is the normalized laser frequency which is bounded from above, $x < 2+2\sqrt{2}$, in order not to loose the photon beam by soft e^+e^- pair production. A PLC should therefore provide us with measurements which cannot be matched by the other experiments. Formation of squark-onia, precision measurements of SUSY particle properties, and measurements of CP violation in the chargino sector are examined. In the $e\gamma$ mode, single production of s-electron in association with a neutralino may turn out to be the best laboratory of s-lepton flavor physics. The e^-e^- mode can be the precision SUSY factory if s-electron pair can be produced.

In section 4, I give a few remarks on the role of a PLC in the study of the properties of the SM particles and their interactions. Such studies could be the main theme of high energy physics if neither the LHC nor e^+e^- collider fail to identify the physics beyond the SM. I also emphasize the importance of preparing all the SM background simulation programs in the helicity amplitude level so that they can be simulated for arbitrary polarization of the colliding photons.

Throughout this report, I use a very simple approximation to a PLC where the Compton scattering formula is used to generate colliding photons in the exactly backward direction. This description gives a good approximation only for the hard part of the photon beams[10,11]. In Fig. 1, I show the normalized effective luminosity function

$$\frac{1}{L_{\gamma\gamma}}\frac{dL_{\gamma\gamma}}{d\sqrt{\tau}} \tag{2}$$

in this approximation for four values of the laser frequency parameter x, $x = 2+2\sqrt{2}$, 1.6, 0.8 and 0.4 from the right to the left, and for three cases of the electron and laser polarizations, (a) to (c). Only the region where $\sqrt{\tau}/\sqrt{\tau}_{\max} > 0.75$ are shown, where the approximation may hold. In (a) and (b), circularly polarized laser beams ($P_c = \pm 1$) are used to make collisions of definite helicity photons, and the luminosity distribution is given for the

collision of two right-handed photons $(++)$, denoted by solid lines, that of right- and left-handed photons $(+-)+(-+)$, denoted by long-dashed lines, and that of two left-handed photons $(--)$, denoted by short-dashed lines. In (a), both photons are obtained by setting $P_eP_c=-1$, whereas in (b) they are obtained by setting $P_eP_c=-P_e=-0.8$, as a more realistic case. Although the laser light may be 100% circularly polarized ($|P_c|=1$), the colliding e^-e^- beams have finite polarization. It is worth noting here that nearly optimal monochromaticity of the colliding photon polarizations is obtained with the electron beam polarization of $|P_e|=0.8$ which may well be realized. The curves in (c) are obtained for $P_e=0$ and $P_t=1$ when the two laser photons have parallel linear polarization. Here P_t stands for the degree of linear polarization. Solid lines show collisions when two photons have parallel linear polarizations, and dashed lines are for perpendicular linear polarizations. The former two-photon state is CP-even while the latter state is CP-odd. We can clearly see that capability of distinguishing the two cases is small for high laser frequencies (x) or when $\sqrt{\tau}\gtrsim 0.6$.

Before closing this section, I should note that the actual luminosity function may depend strongly on the property of the incoming electron beams and on the electron-to-photon conversion efficiency. We may express

$$\frac{dL_{\gamma\gamma}}{d\sqrt{\tau}}=\kappa^2 L_{ee}^{\rm geom}\left(\frac{1}{L_{\gamma\gamma}}\frac{dL_{\gamma\gamma}}{d\sqrt{\tau}}\right), \tag{3}$$

$$\frac{dL_{e\gamma}}{d\sqrt{\tau}}=\kappa L_{ee}^{\rm geom}\left(\frac{1}{L_{e\gamma}}\frac{dL_{e\gamma}}{d\sqrt{\tau}}\right), \tag{4}$$

where $\sqrt{\tau}=\sqrt{s_{\gamma\gamma}}/\sqrt{s_{ee}}$ in Eq. (3) while $\sqrt{\tau}=\sqrt{s_{e\gamma}}/\sqrt{s_{ee}}$ in Eq. (4). $L_{ee}^{\rm geom}$ is the geometric luminosity of the colliding e^-e^- beams in the absence of beam-beam effects, and κ denotes the conversion factor of order 0.5. Because the geometric luminosity can be significantly larger than actual collision luminosity in the e^+e^- or e^-e^- modes, there is a possibility that the luminosity integrated over the high $\sqrt{\tau}/\sqrt{\tau}_{\rm max}$ region shown in Fig. 1 can be comparable or even larger than the corresponding luminosity of e^+e^- collisions. When we compare physics capability of a PLC with its parent e^+e^- or e^-e^- LC, I assume that the integrated $\gamma\gamma$ luminosity in the high $\sqrt{\tau}/\sqrt{\tau}_{\rm max}$ region is about the same as the luminosity of e^+e^- collisions.

It should be remarked here that the luminosity distributions as shown in Fig. 1 do not include contributions from the beamstrahlung. At a PLC, since the electron beams are tuned to maximize the $\gamma\gamma$ luminosity, more beamstrahlung may be produced than in the corresponding e^+e^- collisions. It is therefore important to estimate the effects of beamstrahlung in all quantitative studies, especially in the relatively low $\sqrt{\tau}$ region where we expect to have high degree of linear polarization transfer.

2 Neutral Higgs bosons

A PLC associated with a 500 GeV e^+e^- LC will have the strongest case when a light Higgs boson exists below 200 GeV. Despite failures of discovering the Higgs boson so far, this is the most favored scenario of particle physics at the moment, because it is favored by the electroweak precision measurements[12], and because it is predicted by all supersymmetric theories with grand unification of the three gauge couplings[13]. Such a Higgs boson may still be found at LEP200 or at Tevatron if its mass is very near to the present lower mass bound ($\sim$ 110GeV) and if it has nearly maximum coupling to the W and Z bosons. It should certainly be discovered at LHC through gluon-gluon or WW/ZZ fusion, unless its couplings to gluons and WW/ZZ are both very small, or if it has little decay branching fractions into all the observable channels, such as $\gamma\gamma$, $\tau^+\tau^-$ and WW^*/ZZ^*. It should be definitely discovered at an e^+e^- LC as long as it has a significant coupling to the W and Z bosons, the condition which is required for a good fit to the electroweak data [1] and for the perturbative unification of the gauge couplings in SUSY models.

A 500 GeV LC will measure its couplings to Z and W bosons very accurately, and measure its decay branching fractions[14], Br(bb), Br($\tau^+\tau^-$) and Br(WW^*) with a good accuracy, as well as Br(cc) and Br(gg). The PLC will in addition measure the partial width $\Gamma(H \to \gamma\gamma)$ at a few % level[7,8]. Because the $H\gamma\gamma$ coupling receives contributions from all the massive charged particles that couple to the Higgs boson, its accurate measurement will give us decisive information on the scalar sector when combined with accurate measurements in e^+e^- collisions. For instance, by using the couplings that are measured in e^+e^- collisions, one may estimate the Higgs coupling to the top-quarks and other new states by using the $\Gamma(H \to \gamma\gamma)$ data.

I note in passing that the Higgs-$Z\gamma$ coupling can be most accurately measured in the $e\gamma$ collision mode of a PLC[9]. It is clear that accurate knowledge of both the Higgs-$\gamma\gamma$ and the Higgs-$Z\gamma$ couplings will be powerful in probing the quantum numbers of the charged particles whose masses originate from the electroweak symmetry breakdown.

In addition, I would like to emphasize the importance of the CP measurements in the scalar sector. Because the gauge interactions do not allow CP violation, [2] non-gauge interactions should be responsible for the observed CP violation, and ultimately, for the origin of the matter dominated universe. The non-gauge

[1] Otherwise, there should be some sort of cancellation between the heavy Higgs boson and new physics contributions to the precisely measured electroweak parameters.

[2] Disregarding the CP-odd vacuum angle of QCD, whose effect is known to be negligibly small.

interactions among scalar bosons and between scalars and fermions are among the most likely sources of CP violation, and precise measurements of the CP properties of the Higgs bosons and their interactions may open a completely new road in our investigation. The PLC will be an excellent laboratory for CP violation in the scalar sector, because it allows us to prepare the $J_z = 0$ initial states with definite CP parity. By denoting the two colliding photon helicities as λ_1 and λ_2, the CP transformation changes their signs

$$\mathbf{CP}\,|\,\lambda_1,\,\lambda_2\rangle = |\,-\lambda_1,\,-\lambda_2\rangle \tag{5}$$

and hence the two states with definite CP parity are obtained as

$$\mathbf{CP}(\,|{++}\rangle \pm |{--}\rangle\,) = \pm\,(\,|{++}\rangle \pm |{--}\rangle\,)\,. \tag{6}$$

The CP-even state has two linearly polarized photons with the polarization planes parallel, while the CP-odd state has perpendicular linear polarization directions. If CP is a good symmetry of the scalar sector, the CP-even Higgs boson can couple only to the CP-even initial state, whereas the CP-odd Higgs boson can couple only to the CP-odd initial state.

In Fig. 1(c), I show the $\gamma\gamma$ luminosity when the two laser beams are both linearly polarized ($P_t = 1$) along the same direction in the perfect backward scattering configuration. The Compton scattering with unpolarized e^-e^- beams then produces collisions of high energy linearly polarized photons which are partially CP-even (parallel, or $\|$) and partially CP-odd (perpendicular, or $\perp$). When the initial laser polarization planes are made to the perpendicular orientation, the luminosity functions of the CP-even and CP-odd configurations are reversed. We note that in this simple Compton scattering scheme, the difference between CP-even and CP-odd luminosity functions is significant only for relatively low laser frequencies ($x \lesssim 1.6$) or at relatively low $\gamma\gamma$ invariant mass, $\sqrt{\tau} \lesssim 0.6$. The linear polarization of the PLC will hence be useful for studying the CP property of the neutral scalar boson whose mass is less than about 50% of the initial e^-e^- collision energy, $\sqrt{s_{ee}}$. Because of the necessity of relatively low $\sqrt{\tau}$ values to achieve high degree of linear polarization transfer, backgrounds from beamstrahlung photons should be estimated in quantitative studies.

It is worth noting here that it is an easy task for e^+e^- LC to distinguish between a CP-even and CP-odd neutral Higgs bosons. Such discrimination can e.g. be made by a simple angular correlation study in the process $e^+e^- \to ZH$ followed by the decays $Z \to f\bar{f}$[15–17]. What is difficult in the e^+e^- mode is to detect small CP violation effects in the study of dominantly CP-even Higgs bosons. The observable effects are expected to be rather small in e^+e^- collisions because the small CP-odd component can contribute to the

process only in the one-loop order whereas the dominant CP-even component contributes at the tree-level. At a PLC, both components are expected to contribute in the one-loop order, and hence we can generally expect bigger CP asymmetries[18]. The use of the linearly polarized laser light allows us to make the precision CP measurement a counting experiment when the Higgs boson mass is less than about 50% of the e^+e^- collision energy[19]. Although we may need to rely more on the final state decay angular correlation studies for higher mass bosons, the advantage of larger CP asymmetry expected at a PLC will persist for all the neutral spin-less states that couple to the $\gamma\gamma$ channel.

A PLC will be powerful in studying/discovering the neutral Higgs bosons (or its partners) which have suppressed couplings to the Z and W bosons[20]. Such states are expected in multiple Higgs doublet models including the SUSY-SM, and in fact their existence at or below the TeV scale makes the unification of the three gauge couplings possible in the minimal SUSY-SM[21]. The precision electroweak experiments constrain the mass of the Higgs boson which has significant couplings to the W and Z bosons to be less than about 200 GeV, or else there should be subtle cancellation among new physics contributions. The degree of subtleness of this cancellation increases as the mass of the Higgs boson increases. Therefore it is most natural for us to expect that a light Higgs boson of mass in the range $100 \sim 200$ GeV has nearly the maximal couplings to the W and Z bosons, and hence its heavier partners do not have significant couplings to the weak bosons. Such states are difficult to produce singly at e^+e^- collisions, and they can be discovered at a PLC if their masses lie in the range $0.5\sqrt{s_{ee}} \lesssim m_{\rm Higgs} \lesssim 0.8\sqrt{s_{ee}}$.

As an example of how heavier Higgs bosons may be found at a PLC, I show in Fig. 2(a) the cross section of the process

$$\gamma\gamma \to t\bar{t} \tag{7}$$

as a function of the invariant mass of the final state, $m(t\bar{t})$. The cross section is calculated for a 500 GeV e^+e^- LC with the $\gamma\gamma$ luminosity function of Fig. 1(a) at the highest laser frequency ($x = 4.83$). It should be noted that because of the high $t\bar{t}$ threshold ($2m_t/\sqrt{s_{ee}} \approx 0.7$), only the peak region of the $\gamma\gamma$ luminosity functions contributes where the purity of the collisions of right-handed photons (++) is high. The thick short dashed line shows the prediction of QED. The thick solid line (long-dashed line) shows the prediction where a CP-odd (CP-even) scalar boson of mass 400 GeV is produced as an s-channel resonance. For definiteness, we use the MSSM (minimal SUSY-SM) prediction for the total and partial widths of a 400 GeV CP-odd Higgs boson, A[3]. As a

[3] $\Gamma_A = 1.75$ GeV, ${\rm Br}(A \to t\bar{t}) = 0.95$, ${\rm Br}(A \to \gamma\gamma) = 1.5 \times 10^{-5}$ for $\tan\beta = 3$, $m_{\rm SUSY} = 1$ TeV, $M_2 = 500$ GeV and $\mu = -500$ GeV as chosen in ref. [20].

comparison, predictions for the CP-even Higgs boson case are obtained simply by reversing the CP-parity of the state while keeping all the other properties. It is clearly seen that the interference pattern with the QED amplitude is very sensitive to the CP-parity of the resonance.

In fact the whole difference appears in the helicity amplitudes $\gamma_+\gamma_+ \to t_L\bar{t}_L$ where both t and $\bar{t}$ quarks are left-handed. The thick lines show the distributions when all the $t\bar{t}$ helicities are summed up, whereas the thin lines show those when the $t_L\bar{t}_L$ events (denoted as 'LL') are selected. Note, however, that even though the signal is clearer when the LL events are selected, only those events when one of the W's decay leptonically can be used to distinguish the LL events from the dominant RR events. Still, about 40% of all the $t\bar{t}$ events may be used for such helicity analysis. It may be worth noting here that even the 6-jet events can be used to distinguish between the LL+RR modes and the LR+RL modes. In our example, because of suppressed $J_z = \pm 2$ $\gamma\gamma$ luminosity distribution in Fig. 1(a), very small fraction of all the $t\bar{t}$ pairs have the polarization LR+RL.

A more serious problem at a PLC is that the invariant mass of the colliding $\gamma\gamma$ system, $\sqrt{s_{\gamma\gamma}} = m(t\bar{t})$, can only be measured through the final top-quark momentum measurement. Accurate knowledge of the top-quark mass and their decay properties which will be obtained in the e^+e^- collision experiments will be used to refine such measurements. Fig. 2(b) shows the $m(t\bar{t})$ distributions when a Gaussian smearing with the error

$$\Delta m(t\bar{t}) = 3 \text{ GeV} \tag{8}$$

is applied. Comparisons between the distributions of Fig. 2(a) and Fig. 2(b) show that the sharp peaks and dips in the original curves are smeared out and accurate knowledge of the measurement error, $\Delta m(t\bar{t})$, will be needed to determine the mass and the widths of the Higgs resonances. The quoted error of 3 GeV may be too optimistic especially for semi-leptonic modes where at least one hard neutrino is missing. More work is needed to make the error as small as possible, for both 6-jet and semi-leptonic modes.

From Fig. 1(c), we find that linearly polarized laser beams produce little CP discriminating power at large x, or at large $\sqrt{\tau}$. When a scalar resonance is found in the mass range of $0.6 \lesssim m_{\rm res}/\sqrt{s}_{ee} \lesssim 0.83$, we should refer to the final state analysis to determine its CP property. As an example of CP-sensitive observables, I show in Fig. 2(c) the $m(t\bar{t})$ dependences of $\langle \sin \Delta\phi \rangle$, where $\Delta\phi$ stands for the difference of the azimuthal angles of the t-decay and $\bar{t}$-decay planes along the $t\bar{t}$ momentum axis. The thin lines are predictions before smearing and the thick lines after smearing with the error of Eq. (8). The asymmetry has opposite signs between the CP-odd and the CP-even resonances, whose predictions are shown by the solid and the long-dashed curves,

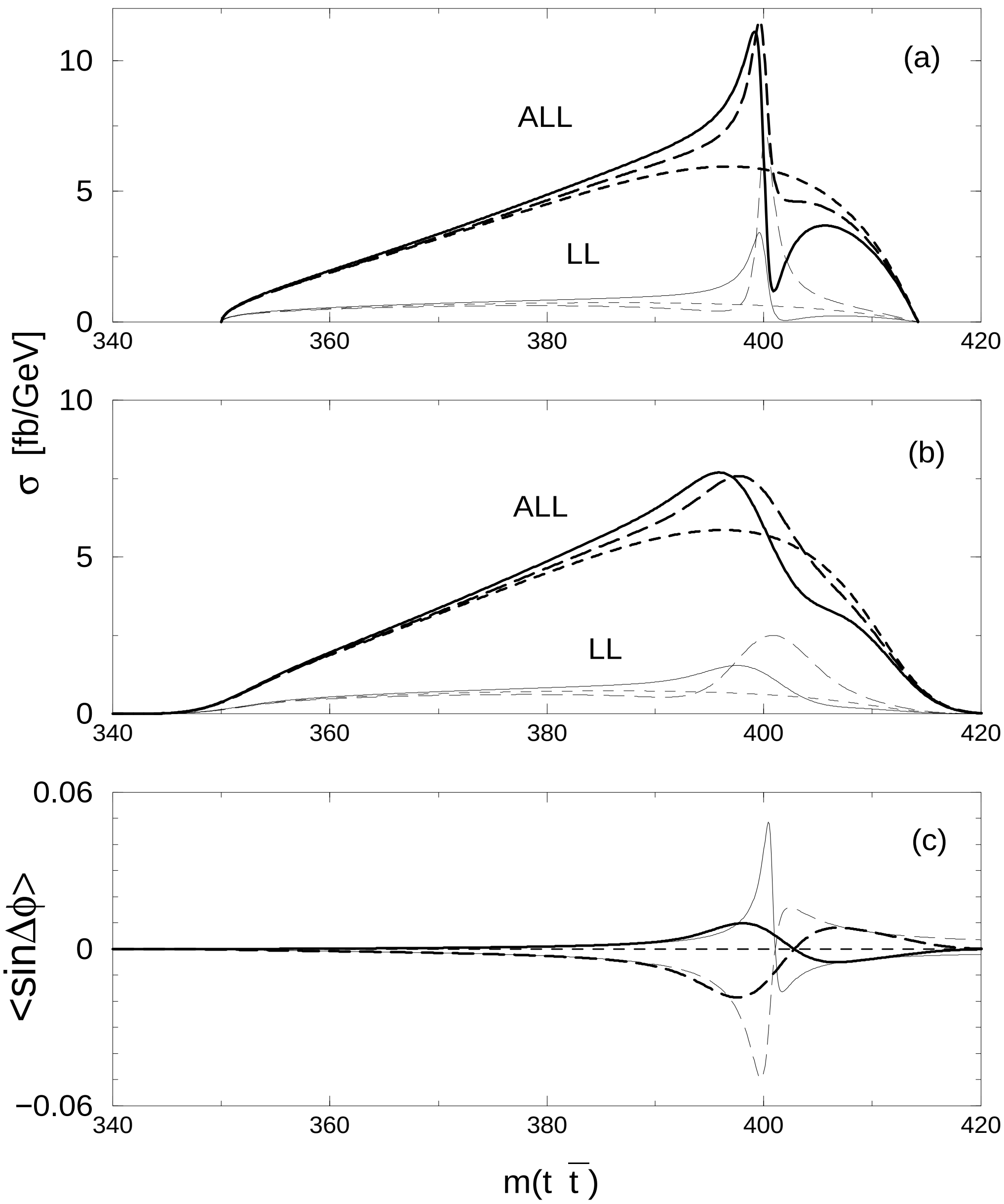

Fig. 2. The cross section of $\gamma\gamma \to t\bar{t}$ events as a function of $m(t\bar{t})$ for the $\gamma\gamma$ luminosity of Fig. 1(a) for $x = 4.83$ at $\sqrt{s}_{ee} = 500$ GeV. Short-dashed curves show QED predictions, while solid (long-dashed) curves show predictions when a 400 GeV CP-odd (CP-even) spin-less resonance is produced in the s-channel. In (a) and (b), the thick lines are for total events and the thin lines are for events where both t and $\bar{t}$ are left-handed. Gaussian smearing with $\Delta m(t\bar{t}) = 3$ GeV is applied in (b). Azimuthal decay angular correlation is shown in (c) with (without) the smearing by thick (thin) lines.

respectively. The asymmetry is found to be rather small because of cancellation between the contributions from longitudinally and transversally polarized W's. One can certainly find final-state observables which have significantly higher sensitivity to the CP-properties of the resonance, by taking account of the W-decay distributions.

In summary, if the resonance mass is low enough, say $m_{\rm res}/\sqrt{s}_{ee} \lesssim 0.6$, we can use the linear polarization of laser beams to determine its CP property. If the resonance has significant decay branching fraction into spinful heavy particles, such as $t\bar{t}$ or W^+W^-/ZZ, it is relatively easy to determine its CP property by making use of the decay angular correlations. Only when the mass is in the range $0.6 \lesssim m_{\rm res}/\sqrt{s}_{ee} \lesssim 0.83$ and when it rarely decays into heavy spinful particles, we will have difficulty in determining its CP property. The possibility of giving high degree of linear polarization to the colliding high-energy photons, that has been discussed at this workshop[22] may turn out to be useful in such cases. I also feel that more serious work may be needed to determine if the $\tau^+\tau^-$ decay mode of a heavy resonance can be used to study its spin and CP-parity at a PLC. In general, it is important to make CP measurements at all possible channels, so that we can probe CP-violation in the mixing, in the production, and in various decay channels[23].

3 SUSY particles and charged Higgs bosons

At a PLC, we can produce a pair of squarks, sleptons, charged Higgs bosons and charginos above the threshold. Because the $\gamma\gamma$ collision at a PLC can reach the c.m. energy of at most about 80% of the corresponding e^+e^- collision energy, it is unlikely that these particles are discovered at a PLC. The question is what advantage does a PLC have over its parent e^+e^- LC when studying their properties.

In case of squarks, sleptons and charged Higgs bosons, we note that the pair can be produced in the s-wave at a PLC, whereas the pair can only be produced in the p-wave near threshold at e^+e^- collisions[4]. This can lead to a higher production rate at a PLC depending on the factor of $\kappa^2 L_{ee}^{\rm geom}$ in Eq. (3). It is possible that the production rate larger than that at the parent e^+e^- LC can be achieved at a PLC if the factor of $\kappa^2 L_{ee}^{\rm geom}$ can be made significantly larger than the actual e^+e^- luminosity. In such cases, precision measurements of the charged scalar boson properties may be performed at a PLC. In addition,

[4] The exception to this rule is the production of $\tilde{e}_L^{\pm}\tilde{e}_R^{\mp}$ pairs where the electronic chilarity of the initial channel is transfered to the final state. With proper choice of initial $e^{\pm}$ beam polarizations, these pairs can be produced at s-wave near the threshold.

in case of squarks, we may find the s-wave $J = 0$ squark-onia at a PLC. There might be a case when the squark-pair production is sensitive to the Higgs-boson exchange between stop quarks[24].

In case of chargino-pair production near the threshold, they are produced in the s-wave both in e^+e^- and $\gamma\gamma$ collisions. The only difference is that the pair is in the spin-triplet state in case of e^+e^- collisions while it is in the spin-singlet state at a PLC. I do not know if this difference leads to a significant difference in the study of their properties. Because the s-wave spin-singlet state is CP-odd, a PLC may be useful in probing the CP property of the chargino-photon couplings. This however requires a PLC with relatively low laser frequencies (hence a higher e^+e^- energy), and the sensitivity should be compared with that of the final state analysis in the e^+e^- mode[25,26].

There is one point which might be worth noting. Both the sfermion-pair and chargino-pair production cross sections are uniquely determined by QED in the leading order of $\gamma\gamma$ collisions. This uniqueness of the tree-level amplitudes may help us identify radiative effects. Certainly a combination of precision measurements of production cross sections at both e^+e^- and $\gamma\gamma$ collisions will give us useful additional information on the interactions of the SUSY particles and the charged Higgs bosons.

Finally, the $e\gamma$ collision mode of a PLC may become a unique laboratory of slepton flavor physics[27] if $\tilde{e}_L$ or $\tilde{e}_R$ ($\tilde{\nu}_{eL}$) can be produced in association with a neutralino (chargino). Flavor oscillation in the slepton sector can be most clearly studied in this channel where a SUSY particle state with a definite flavor and chilarity quantum numbers can be produced at the time of collisions.

Before concluding this section, let me comment on the possibility of precision SUSY tests in the process[28] $e^-_\alpha e^-_\beta \to \tilde{e}^-_\alpha \tilde{e}^-_\beta$ for the three distinct channels, $\alpha\beta = LL$, RR and LR. The process is most suited for precision measurements of the s-electron masses and their couplings to the gauginos, which may give us precious information on the heavy SUSY particle masses[29,30,28]. Dedicated study of the e^-e^- collider option is worth serious attention, which requires studies independent of the e^-e^- beams which are optimized for the PLC option.

4 The Standard Model

When we consider the SM processes as a probe of new physics, I think that a PLC can have an advantage over its parent e^+e^- LC when we study in detail the $J = 0$ channel, by using the monochromaticity of high $\sqrt{\tau}$ region with high laser frequency, or when we study the CP property by using the linear

polarization with relatively low laser frequency. Measurements of W and top-quark EDM[31] are examples of the latter. As for the $J = 0$ channel, ZZ[32], W^+W^-[33] and $t\bar{t}$[34] final states are all important because they should couple to the electroweak symmetry breaking sector to obtain their masses. That the electroweak precision measurements favor the SM Higgs boson of mass below about 200 GeV implies that if the Higgs boson (whose coupling to W and Z bosons are significant) is much heavier than 200 GeV or absent, there should be new physics that couple to W and Z bosons. Because it should affect the W and Z properties significantly, we should be able to identify its effect at LHC or at a lepton collider. The combined study of the $J = 1$ channel at e^+e^- LC and the $J = 0$ channel at a PLC may be most fruitful in the search of such new interactions.

I would like to note also that detailed studies of purely neutral gauge boson scattering processes, $\gamma\gamma \to \gamma\gamma$, $Z\gamma$ and ZZ, may give us useful information on new physics that affect these channels either in the tree-level or through radiative effects. The complete helicity amplitudes for all these mode in the SM are known[35] and they should be useful in determining the properties of new physics that affect these processes.

The SM processes are also important for monitoring of the luminosity and the polarization of colliding photons, and also as backgrounds in new particle studies. Because we will need both circular and linear polarization of laser light, it is important for us to prepare all the SM simulation tools in the helicity amplitude level. All the SM processes should be generated for an arbitrary set of the Stokes parameters of the incoming photons. For instance, since massless leptons and quarks cannot be produced at large scattering angles from $J_z = 0$ two photons in the lowest order of QED, $J_z = 0$ luminosity functions may be monitored by using higher order processes, such as $l^+l^-\gamma$, $l^\pm\gamma(l^\mp)$ and $l^+l^-l'^+l'^-$, or by using W^+W^-[36]. Hadron jet shape from $\gamma\gamma \to q\bar{q}(g)$ processes may also be sensitive to the ratio of $J_z = 0$ and $J_z = \pm 2$ collisions because we expect $J_z = 0$ photons to produce fatter jets. The $J_z = 0$ luminosity function may be measured more efficiently by reversing the laser and electron polarizations simultaneously but in one side only, which leaves all the distributions the same while replacing the $J_z = 0$ and $|J_z| = 2$ distributions[37]. Linear polarization may be monitored by azimuthal angle distributions of high p_T l^+l^- events. All these studies should be done in the presence of realistic beamstrahlung backgrounds in order to estimate the monitoring errors.

5 Conclusions

If a light Higgs boson of mass below 200 GeV is found, a PLC should be built in association with the first stage of an e^+e^- LC at about 500 GeV collision

energy. Precision measurements of its $\gamma\gamma$ width and its CP property and the search for its high mass partners are the main targets of the PLC. If a Higgs boson is not found or found at a significantly higher mass, I think that a PLC will be most powerful when combined with the highest-energy e^+e^- LC. Studies of the processes $\gamma\gamma \to ZZ, W^+W^-, t\bar{t}$ in the $J = 0$ channel at highest $\gamma\gamma$ collision energies with high laser frequencies, and precise measurements of W and top-quark properties at low laser frequencies may be most fruitful in discovering new physics in such cases.

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